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Key Performance Indicators for Residential District Energy Systems: A Framework for Economically Motivated Assessments

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Abstract:

As renewable energy sources become more prevalent, local electricity and heat generation becomes increasingly important, underscoring the significance of district energy systems. Residential districts, in particular, have advantages over building-level supply systems. The temporal variation in demand reduces peaks, and the higher aggregated loads facilitate the integration of diverse technologies and energy sources. However, designing and operating such systems requires balancing economic, ecological, and technical objectives. Robust, well-defined key performance indicators (KPIs) are essential for evaluating and comparing energy concepts. Although numerous KPIs are used in research and practice, their definitions, interpretations, and stakeholder relevance are often unclear. An overabundance of metrics can blur priorities and obscure which measures are truly relevant to decision-making.

Building on largely generic literature, we synthesize and propose a stakeholder-specific KPI framework for those implementing the energy transition in residential districts, shifting the focus from a generic view to the actual decision-makers in district energy systems, namely economically driven housing companies and housing cooperatives. We analyze their motivations and objectives and select KPIs that reflect them. The framework identifies and prioritizes the KPIs that are most relevant to these stakeholders. It organizes these KPIs into primary and secondary indicators. Primary KPIs directly inform investment decisions, while secondary KPIs provide additional insight into system performance, though they are not decisive for investments. We concentrate on the planning phase, as choices made then shape outcomes over the next 20-30 years. We also discuss emerging metrics for flexibility and sector coupling. Instead of simply listing indicators, we examine their interdependencies and present a coherent set of KPIs aligned with investor objectives.

By clarifying KPI definitions and their links to planning goals, the framework enables transparent, comparable, and goal-consistent evaluations, supporting more robust investment decisions. The framework also contributes to academic and policy debates by revealing incentives and helping to design policies that align private actions with socially beneficial outcomes.

Keywords:
District Energy Systems; **Key Performance Indicators**; **Housing companies**

1. Introduction

Districts have emerged as an important unit of action in the energy transition. Compared to individual buildings, districts provide unique opportunities for developing energy systems: The aggregation of multiple buildings leads to reduced simultaneity effects, smoothing demand peaks, and enabling the deployment of technologies that are infeasible or uneconomical at the single-building scale. At the same time, district-level energy systems require sophisticated planning and operation to balance economic viability, ecological responsibility, and technical performance, objectives that often interact in complex and sometimes conflicting ways. Understanding and navigating these trade-offs is therefore essential for future district energy systems. Evaluating new concepts for district energy systems requires suitable indicators capable of making these trade-offs transparent. Key performance indicators (KPIs) provide this foundation: they allow researchers, planners, and practitioners to compare design options, assess applicability across contexts, and communicate performance in a structured and comprehensible way. In recent years, several contributions have explored KPI repositories, selection frameworks, and multi-criteria assessment approaches for building- and district-level energy systems.

Amini Toosi et al. [1] conducted a comprehensive literature analysis of KPIs describing the interaction between buildings and the electricity grid. They identified several clusters of KPIs, technical (energy efficiency, energy flexibility, renewable integration, grid integration), environmental, economic, and social clusters and additionally quantified how frequently these categories appear in current research. Angelakoglou et al. [2] developed a KPI repository for building renovation projects using expert interviews supported by a systematic literature review. Their selection of KPIs was based on criteria such as relevance, data availability, measurability, reliability, and familiarity, resulting in a structured list of 69 KPIs representing multiple stakeholder perspectives. Similarly, Krekling Lien et al. [3] proposed a generalizable KPI selection approach that adds scalability and planning-phase applicability to the used selection criteria. Their workflow begins with a broad KPI compilation and employs multi-attribute decision-making (MADM) methods to support systematic selection of KPIs. Other contributions have demonstrated how carefully chosen KPIs can enhance both building and district-level performance. Klobut et al. [4] derived six essential KPIs including Life Cycle Costs, Indoor Air Quality, Thermal Comfort, Climate Impact, Energy Consumption, and On-Site Energy Ratio highlighting their practical relevance for real-world performance improvement. Salom et al. [5] focused explicitly on district-scale zero-emission neighborhoods (ZENs), organizing KPIs into five categories: energy and environmental performance, economic performance, indoor environmental quality, social performance, and smartness/flexibility. They further evaluated the diversity of their selected KPI categories using the Shannon index. Lastly, Efkarpidis et al. [6] proposed a generic KPI framework applicable from single buildings up to regional energy systems, emphasizing smart electricity systems while still considering multi-vector energy flows and providing an extensive discussion of stakeholder objectives ranging from system operators to local authorities and end-users.

While existing contributions provide important assessments, they are largely designed for broad applicability across district concepts, stakeholder groups, and spatial scales. This generality supports top-down analyses of the energy transition but only partially reflects the decision context of those who ultimately implement district energy systems. In practice, investment decisions are made by economically motivated actors, such as housing companies, cooperatives, or private investors, whose choices are shaped by economic objectives, risk considerations, long-term responsibilities, and regulatory conditions. This paper addresses this gap by explicitly adopting the perspective of these implementers and focusing on the planning phase, where long-term investment decisions are made. Building on the generic literature, we develop a KPI framework tailored to residential district energy systems that is aligned with the decision logic of economically oriented actors, while also providing a transparent basis for research and policy analysis.

2. Method

The KPI framework was developed through an iterative process combining literature analysis with stakeholder engagement, progressively narrowing the selection at each step. First, we conducted a literature review to compile a comprehensive set of KPIs used in building and district energy system assessments ([1], [2], [3], [4], [5], [6], [7], [8], [9]). From this broad compilation, we initially selected all KPIs that could be potentially relevant to district energy systems. This set was then narrowed by evaluating each KPI through the lens of economically motivated investors, specifically housing companies and housing cooperatives, drawing on the authors' experience working with such stakeholders. The remaining KPIs were subsequently classified into primary and secondary indicators according to their role in investment decision-making: primary KPIs directly inform investment decisions, while secondary KPIs provide supplementary insights without being decisive for the investment itself. To validate and further refine this selection and classification, we discussed the proposed framework with industry partners, including LEG/ESP within the Future-iQ project as well as smaller housing companies. Based on their feedback, we adapted the framework to accurately represent the decision-making perspective of these actors.

3. Definition of KPI framework

KPIs can be organized along multiple dimensions, including spatial scope (building, district, regional), stakeholder perspective, and thematic category [6]. While generic frameworks aim to accommodate all these dimensions simultaneously, this paper adopts a more targeted approach. We focus on a single stakeholder group, namely housing companies and housing cooperatives (housing sector) and a single spatial scope: the residential district. By narrowing the perspective in this way, we can discuss KPI categories specifically through the lens of those who actually make investment decisions about district energy systems. To structure our framework, we introduce two groups of KPIs: primary and secondary. Primary KPIs are those that directly inform and drive investment decisions. They represent the core metrics that economically motivated actors use to evaluate whether an energy concept is viable and aligns with their business objectives. Secondary KPIs provide additional insight into system performance, such as environmental impact, technical efficiency, or grid interaction, but do not themselves determine whether an investment proceeds. They remain relevant for understanding system behavior or communicating performance to external stakeholders, yet they are subordinate to the primary economic criteria in the decision-making hierarchy.

3.1. Scope of the framework

3.1.1. The stakeholder: economically motivated actor

The primary motivation of these actors is economic: ensuring the financial viability and long-term value preservation of their housing assets. This translates into several interrelated objectives. Housing companies seek to minimize total cost of ownership, encompassing capital expenditure, operational costs, and maintenance over the system lifetime, while securing stable and predictable cash flows to support long-term business planning and debt servicing. Simultaneously, they aim to maintain or enhance the competitiveness of their housing stock in the rental market, which is increasingly linked to energy costs, comfort, and sustainability credentials. Regulatory compliance represents another key objective, as evolving legal requirements impose energy efficiency standards, carbon reduction mandates, and updated building codes. Finally, risk management plays a central role: actors seek to limit their exposure to technological, regulatory, and market uncertainties, particularly given that energy infrastructure investments typically span multiple decades. Beyond these financial considerations, housing cooperatives may also pursue social objectives such as providing affordable housing and fostering community welfare. However, even these social goals remain ultimately constrained by economic sustainability requirements.

3.1.2. The spatial scope: residential district

This framework defines the residential district as the spatial unit of analysis, encompassing all buildings within a delineated area under the management or ownership of the housing actor. The district level offers distinct advantages over building-level analysis: aggregation effects reduce demand peaks through load diversity, enable shared infrastructure, and support technologies that would be uneconomical at smaller scales. We include three energy sectors within the system boundary: heating, electricity, and mobility. This choice reflects the sectors over which housing actors have direct or partial influence.

Heating: The system boundary includes all thermal energy required for space heating and domestic hot water within the district's buildings. Housing actors typically exercise full control over heating infrastructure decisions, making this sector central to their investment planning.

Electricity: The boundary encompasses electricity consumed within the district, including household appliances, lighting, common area services, and increasingly, on-site generation and storage. With the growing deployment of photovoltaic systems and tenant electricity models (e.g. Mieterstrom in Germany), housing actors are transitioning from passive consumers to active participants in electricity supply.

Mobility: The inclusion of mobility requires careful consideration of system boundaries. For conventional vehicles relying on gasoline, energy consumption occurs outside the district and bears limited relevance to district energy planning. However, the electrification of transport fundamentally changes this relationship: electric vehicle (EV) charging within the district becomes an integral component of the energy system.

3.2. Primary KPIs

In the following, we present the selection of primary KPIs that represent the core metrics that economically motivated actors use to evaluate whether an energy concept is viable and aligns with their business objectives. We show their calculation, and the specific investment-relevant objectives they address.

Table 1. *Primary Key Performance Indicators.*

Category	Key Performance Indicator
Profitability	Funds from Operation (FFO)
	Adjusted Funds from Operation (AFFO)
	Internal Rate of Return (IRR)
Tenant expenses	Levelized Costs of Heat (LCOH)
	Warm rent / rent including utilities
	Net rent / rent exclusive of utilities (cold rent)
Emissions	Emission Avoidance Costs
	Avoided Emissions (Total and specific)
	Total GHG emissions

Funds from Operation (FFO) Funds from Operations (FFO) is a cash flow metric that quantifies net operating income. It reflects the difference between revenue from rent or energy sales (e.g. heat and electricity) and operating expenses. Non-cash items, such as depreciation and amortization, are excluded. FFO provides housing companies with a clear indication of their infrastructure's capacity to generate recurring cash. Unlike accounting profit, FFO reflects the actual liquidity available for debt servicing, reinvestment or distribution. For publicly traded companies, positive and stable FFO indicates operational viability and reduces financing risk.

$$FFO = \sum_i R_i - \sum_j O_j \tag{1}$$

R_i Revenue stream *i* (e.g., heat sales, electricity feed-in tariffs)
O_j Operating expense *j* (e.g., fuel costs, maintenance, personnel)

Adjusted Funds from Operation (AFFO) Adjusted funds from operations (AFFO) is a refinement of funds from operations (FFO) that deducts the recurring capital expenditures necessary to maintain the operational capacity of the energy system. These maintenance-related investments, often termed sustaining capital expenditures, are necessary to preserve asset functionality over time. They must be distinguished from expansion-related investments.

$$AFFO = FFO - \sum_k C_k^{maint} \tag{2}$$

FFO Funds from Operation as defined above
C_k^{maint} Maintenance capital expenditure *k* required to sustain system performance

Internal Rate of Return (IRR) The internal rate of return (IRR) is the discount rate at which the net present value (NPV) of an investment's cash flows equals zero. The IRR represents the annualized, effective, compounded return rate that an investment is expected to yield over its lifetime. The IRR enables housing companies to compare the profitability of different energy system configurations on a standardized basis. The IRR directly indicates whether an investment meets or exceeds the company's required rate of return (hurdle rate). A higher IRR relative to alternative investments or the cost of capital indicates economic attractiveness.

$$\sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} = 0 \quad (3)$$

CF_t	Net cash flow in period t (revenues minus operating costs minus investments)
T	Project lifetime (typically 20–30 years for district energy systems)
r	Internal Rate of Return

Levelized Costs of Heat (LCOH) The levelized cost of heat (LCOH) is the average cost per unit of heat delivered over the lifetime of an energy system. It combines cost components such as initial investment, operation and maintenance, fuel, and financing into one metric, enabling comparison across technologies and system configurations. Lower LCOH directly translates to lower heating costs for tenants and higher margins for operators.

$$LCOH = \frac{\sum_{t=0}^{T} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{Q_t}{(1+r)^t}} \quad (4)$$

I_t	Investment expenditure in period t (including initial and replacement investments)
$O\&M_t$	Operation and maintenance costs in period t
F_t	Fuel or energy procurement costs in period t
Q_t	Useful heat delivered in period t (in kWh)
r	Discount rate
T	System lifetime

Warm rent / rent including utilities Warm rent is the total monthly payment that tenants make to housing companies. It includes the basic rent for the dwelling, plus operating costs such as heating, hot water, and other utilities. It reflects the actual housing cost burden experienced by tenants. Warm rent is the decisive metric for tenant affordability, as well as for letting potential and vacancy risk.

$$W = N + \sum_l U_l \quad (5)$$

W	Warm rent (€/month or €/m²·month)
N	Net rent (basic rent excluding utilities)
U_l	Utility cost component l (e.g., heating, hot water, general electricity)

Net rent / rent exclusive of utilities Net rent is the base rent for a dwelling, excluding operating costs and utilities. In some regulatory framework, net rent may increase following energy-related modernization through a legally defined modernization surcharge, subject to caps and tenant protection provisions. It might also be subject to general caps depending on the region.

$$N = N_{base} + \Delta N_{mod} \quad (6)$$

N	Net rent (€/month or €/m²·month)
N_{base}	Baseline net rent prior to modernization
ΔN_{mod}	Modernization surcharge (legally capped, e.g., 8% of apportionable modernization costs annually in Germany)

Emission Avoidance Costs Emission Avoidance Costs (EACs) are the additional costs incurred to avoid one unit of greenhouse gas emissions compared to a reference system. This metric bridges the gap between economic and ecological assessments by expressing environmental performance in monetary terms. EAC allows housing companies to evaluate the cost-effectiveness of emission reduction measures. It also allows for comparison with external benchmarks, such as CO_2 prices, carbon taxes, and subsidy levels. If the EAC is below the current or expected future carbon price, the investment yields ecological and economic benefits (or reduced regulatory risk).

$$EAC = \frac{\sum_{t=0}^{T} \frac{C_t^{new} - C_t^{ref}}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E_t^{ref} - E_t^{new}}{(1+r)^t}} \tag{7}$$

C_t^{new}	Total cost of the new energy system in period t
C_t^{ref}	Total cost of the reference system in period t
E_t^{ref}	Emissions of the reference system in period t
E_t^{new}	Emissions of the new energy system in period t
r	Discount rate
T	Assessment period

Avoided Emissions (Total and specific) Avoided emissions quantify the reduction in greenhouse gas emissions that is achieved by implementing a new energy system compared to a defined reference system. Total avoided emissions express the overall reduction during the assessment period. Specific avoided emissions normalize this reduction by output unit (e.g., kWh, m² of living area, or dwelling).

Total Avoided Emissions:

$$E_{avoided}^{total} = \sum_{t=1}^{T} \left(E_t^{ref} - E_t^{new}\right) \tag{8}$$

Specific Avoided Emissions:

$$e_{avoided}^{specific} = \frac{E_{avoided}^{total}}{\sum_{t=1}^{T} Q_t} \tag{9}$$

E_t^{ref}	Annual emissions of the reference system in period t (t CO_2 or t CO_2-eq)
E_t^{new}	Annual emissions of the new system in period t
Q_t	Useful heat delivered in period t (kWh)
T	Assessment period

Total GHG emissions Total greenhouse gas (GHG) emissions extend beyond carbon dioxide (CO_2). To include all climate-relevant gases, such as methane (CH_4), GHG can be expressed in CO_2-equivalents (CO_2-eq). This conversion uses global warming potentials (GWP), which quantify the relative climate impact of each gas over a specified time horizon, typically 100 years (GWP_{100}). The scope of emissions included depends on the chosen system boundaries. Following the widely adopted GHG Protocol framework, three emission scopes are distinguished. Scope 1 includes direct emissions from combustion processes within the system boundary, such as on-site gas boilers, combined heat and power (CHP) units, and biomass combustion. Scope 2 includes indirect emissions from the generation of purchased energy (e.g., electricity from the grid or district heating from external suppliers). Scope 3 includes indirect emissions that occur along the value chain. These include embodied emissions from manufacturing, transporting, and installing system components, as well as upstream emissions from fuel extraction and processing.

$$E_{GHG}^{total} = E_{GHG}^{emb} + \sum_{t=1}^{T} \sum_c \sum_g \left(D_{c,t} \times ef_{c,g,t} \times GWP_g\right) \tag{10}$$

E_{GHG}^{emb}	Embodied GHG emissions from system components (in CO_2-eq)
$D_{c,t}$	Demand for energy carrier c in period t
$ef_{c,g,t}$	Emission factor of gas g for energy carrier c in period t
GWP_g	Global Warming Potential of gas g (e.g., CH_4: 28–30 for GWP_{100})
g	Greenhouse gas species (CO_2, CH_4, etc.)

T	System lifetime

3.3. Secondary KPIs

In the following, we outline the selected secondary key performance indicators (KPIs) and describe the objectives they serve for an economically motivated investor. These secondary KPIs enrich the assessment of the system by capturing aspects such as environmental performance, technical efficiency, and interactions with the energy system infrastructure. Although they do not determine whether an investment is ultimately pursued, they provide valuable context for understanding system behavior and support the communication of results to external stakeholders. As such, they complement, but do not override, the primary economic criteria guiding investment decisions.

***Table 2**. Secondary Key Performance Indicators*

Category	**Key Performance Indicator**	**Objective**
Costs	Total Costs (TOTEX), t*otal and annual* Capital Costs (CAPEX), *total and annual* Operational Costs (OPEX), *maintenance* Operational Costs (OPEX), *operation*	A better understanding of the cost structure
Refurbishment	Specific heating demand Building value after refurbishment	Market value
RES Matching Factor	Electrical self-sufficiency rate Total self-sufficiency rate Electrical self-consumption rate Total self-consumption rate	Reduced dependency on energy prices Illustration of investment profitability
Pollution	Noise pollution Air pollution Other pollution	Meet Regulation Requirement
Planning	Hands-off period	Reduced “Mental Load”
Peak Load	Electrical peak load	Risk of having to invest in enhanced grid connection
Grant Coverage	Share of total project costs covered by grants Share of capital costs covered by grants	Improve profitability and enabling new/risky approaches

Total Costs (TOTEX): Total and Annual. TOTEX represents the sum of all capital and operational expenditures over the system lifetime. While profitability metrics such as NPV already incorporate total costs, reporting TOTEX separately provides transparency and facilitates comparison across different energy concepts.

Capital Costs (CAPEX): Total and Annual. CAPEX encompasses all upfront investment costs for equipment, installation, and infrastructure. For housing companies, understanding CAPEX is essential for assessing financing requirements and liquidity constraints, even though the investment decision itself is based on overall profitability.

Operational Costs (OPEX): Maintenance-related. Maintenance-related OPEX includes regular servicing, repairs, and component replacements over the system lifetime. Housing companies require visibility into these costs to plan maintenance budgets and assess long-term operational burden.

Operational Costs (OPEX): Operation-related. Operation-related OPEX covers ongoing expenses such as energy procurement, personnel, and administrative costs. Separating these from maintenance costs allows housing companies to identify cost drivers and potential savings in daily operations.

Specific Heating Demand: Specific heating demand quantifies the thermal energy required per square meter of floor area. This indicator serves as a proxy for building efficiency and is often tied to regulatory requirements that must be met during new construction or refurbishment.

Building Value after Refurbishment: This KPI estimates the asset value following energy-related upgrades. For housing companies, increased building value can improve balance sheet metrics and borrowing capacity, providing an additional economic rationale for refurbishment investments.

Electrical Self-Sufficiency Rate: The electrical self-sufficiency rate measures the share of electricity demand met by on-site generation. A higher rate reduces dependence on external energy prices, thereby mitigating exposure to market volatility.

Total Self-Sufficiency Rate: The total self-sufficiency rate extends this concept to all energy carriers, including heat and electricity. It indicates the overall independence from external energy supply and associated price risks.

Electrical Self-Consumption Rate: The electrical self-consumption rate quantifies the share of on-site generated electricity consumed locally rather than fed into the grid. While revenues from both self-consumption and feed-in are captured in profitability KPIs, this rate provides an intuitive illustration of how effectively local generation is utilized.

Total Self-Consumption Rate: The total self-consumption rate extends self-consumption measurement across all energy carriers. It offers a comprehensive view of how well on-site generation aligns with total energy demand within the district.

Noise Pollution: Noise pollution captures acoustic emissions from energy system components such as heat pumps or ventilation units. Housing companies must consider noise levels to ensure tenant comfort and comply with local regulations.

Air Pollution: Air pollution measures local emissions of pollutants such as particulate matter or nitrogen oxides. While CO_2 emissions are typically the primary environmental concern, local air quality can affect tenant health and may be subject to regulatory limits.

Other Pollution: This category encompasses additional environmental impacts such as visual intrusion or vibration. These factors can influence tenant acceptance and may constrain technology choices in sensitive residential settings.

Hands-off Period: The hands-off period denotes the timeframe during which the energy system operates without requiring major reinvestment or intervention. For housing companies, a longer hands-off period reduces management effort and provides planning security for other portfolio activities.

Electrical Peak Load: Electrical peak load indicates the maximum instantaneous power demand of the district. Peak loads determine grid connection capacity requirements and associated costs, making this metric relevant for infrastructure sizing and cost planning.

Share of Total Project Costs Covered by Grants: This KPI expresses the proportion of total project costs offset by public subsidies or grants. Higher grant coverage directly improves project economics and reduces the capital that housing companies must finance independently.

Share of Capital Costs Covered by Grants: This indicator specifically measures grant coverage relative to upfront capital expenditures. It highlights the extent to which subsidies alleviate initial investment barriers, which is particularly relevant for capital-constrained housing companies.

4. Discussion

In this section, we discuss our selected KPIs, why we placed them in their respective categories (primary or secondary), and why we did not include certain KPIs. The proposed framework deliberately narrows the KPI landscape to those indicators that reflect the decision logic of economically motivated housing actors. This selectivity, however, raises important questions about which metrics are excluded, why they are absent, and what implications this carries for both practice and policy. A number of KPIs that feature prominently in the generic literature are not included in this framework. Notable examples include indicators for energy demand or on-site renewable energy production. Their absence does not imply that these metrics are technically irrelevant. Rather, it reflects the fact that economically motivated housing actors lack an intrinsic incentive to optimize for them. A housing company will not voluntarily minimize grid feed-in peaks or maximize primary energy efficiency if doing so does not improve profitability, reduce costs, or fulfill a regulatory requirement. This observation carries a significant policy implication. If certain system-level objectives, such as grid-supportive behavior or primary energy reduction, are deemed socially desirable, they must be translated into regulatory requirements, financial incentives, or market signals that create a business case for the housing sector. The framework thus serves a dual purpose: it transparently documents what housing actors optimize for, and, by contrast, it reveals which socially beneficial outcomes require external intervention to materialize.

Having established the purpose and rationale of the framework, we now turn to the individual primary KPIs and discuss why each was selected and how it serves the decision logic of housing actors. A deliberate choice within the framework is the selection of the Internal Rate of Return (IRR) as the central profitability metric, rather than the Net Present Value (NPV) or the simple or discounted payback period. All three metrics are fundamentally rooted in discounted cash flow analysis and, in principle, describe similar economic characteristics of an investment. However, in practice, their communicability and usefulness differ considerably. The IRR expresses profitability as a single annualized percentage, which allows for immediate comparison against a company's hurdle rate or cost of capital. It is intuitively understood by financial decision-makers and does not require agreement on an external discount rate for its computation. The discount rate is, in fact, the result. By contrast, the NPV yields an absolute monetary value whose interpretation depends on the chosen discount rate and project scale, making cross-project comparisons less straightforward. The payback period, while simple, ignores cash flows beyond the payback horizon and therefore fails to capture the long-term value of energy infrastructure investments, which typically span 20–30 years. For these reasons, the IRR was identified as the most concise and decision-relevant profitability indicator in discussions with housing companies and is therefore prioritized in this framework.

For housing companies, the provision of heat has traditionally been the only energy service they are obligated to deliver. Heat supply is therefore deeply embedded in their operational and business model, making the Levelized Cost of Heat (LCOH) a natural and well-established KPI. However, the energy landscape in residential districts is changing. The growing deployment of rooftop photovoltaic systems, combined with tenant electricity models such as the German *Mieterstrom* scheme and emerging net metering approaches, positions housing companies as active participants in electricity supply. Similarly, the proliferation of electric vehicles and the installation of charging infrastructure within residential districts opens the door to mobility-related energy services. These developments suggest that the Levelized Cost of Electricity (LCOE) and the Levelized Cost of Charging (LCOC) will gain importance as additional KPIs in the near future. They would enable housing companies to evaluate new revenue streams and business models on a comparable, technology-neutral basis. While these metrics are not yet included as primary KPIs in the current framework, reflecting the present state of practice, their emergence is anticipated and should be monitored in future revisions. It is important to note, however, that these new business models pose a substantial challenge, particularly for smaller housing companies and cooperatives. Unlike large, publicly listed housing corporations, smaller organizations often lack the dedicated personnel, technical expertise, and administrative capacity to manage electricity sales contracts, billing systems, or EV charging operations. They are therefore likely to depend on external partners, such as energy service providers or specialized contractors, to develop and operate these new business areas. As a result, the transition from pure heat provision to multi-service energy supply will likely proceed at a significantly slower pace for smaller actors, and the practical relevance of KPIs such as LCOE and LCOC will grow unevenly across the sector.

A notable inclusion in the primary KPI set is the addition of warm rent and net rent (cold rent), which are not typically found in KPI frameworks for district energy systems in the academic literature. This choice was directly informed by interviews with housing companies and cooperatives during the framework development process. From an academic or engineering perspective, rent levels may appear to lie outside the scope of energy system assessment. However, from the housing company's perspective, rent is the central interface between energy system investment and business viability. Every energy-related decision ultimately manifests in one or both rent components: modernization measures may increase the net rent through legally defined surcharges, while changes in heating technology or fuel costs directly affect the warm rent through the utility cost allocation. Housing companies consistently emphasized that any energy concept is evaluated not only in terms of return on investment but also in terms of its impact on tenant affordability and, consequently, on vacancy risk and letting potential. A system configuration that yields attractive returns but pushes warm rent beyond locally acceptable levels will not be pursued, as it threatens the occupancy rates on which the entire business model depends. Conversely, a concept that stabilizes or reduces the warm rent strengthens tenant retention and market competitiveness. For these reasons, warm rent and net rent function as binding constraints and, in practice, as decision-relevant metrics on par with profitability indicators. Their inclusion as primary KPIs reflects the reality of investment decision-making in the housing sector, even where the academic literature has not yet systematically recognized them as energy system performance indicators.

We now turn to the secondary KPIs, which provide valuable context for understanding system behavior and support communication, but do not themselves determine whether an investment proceeds. A first observation concerns the classification of CAPEX, OPEX, and TOTEX as secondary rather than primary KPIs. This may appear surprising, as these cost metrics are among the most frequently reported indicators in the energy systems literature and are often used as optimization objectives in energy system planning studies. However, from the investor's perspective, absolute cost figures alone are insufficient to inform an investment decision. To arrive at decision-relevant profitability metrics such as the IRR, cost data must be combined with project-specific parameters including the project lifetime, financing structure, expected revenue streams, discount rates, and regulatory conditions. These parameters are specific to each investor and each project, which is precisely the reason why derived profitability metrics such as IRR are rarely reported in academic publications. In practice, however, housing companies do not base investment decisions on CAPEX or TOTEX alone; these figures serve as intermediate inputs that must be processed further before they become decision relevant. The framework reflects this reality by retaining cost metrics as secondary KPIs that provide transparency into the cost structure while positioning the derived profitability indicators as primary.

Among the remaining secondary KPIs, "building value after refurbishment" deserves particular emphasis due to its frequent omission in energy system analyses. Many studies evaluate the economic merit of envelope refurbishment or energy system upgrades solely by comparing investment costs against operational energy savings. When the resulting payback periods appear unfavorable, the conclusion is often drawn that the measure is not cost-effective. This perspective, however, neglects a fundamental economic reality: energy-related modernization increases the asset value of the building. Improved insulation standards, modern heating systems, and higher energy performance certificates contribute to higher market valuations and improved balance sheet positions. For publicly listed housing companies in particular, portfolio value is a critical financial metric that influences borrowing capacity, investor confidence, and share price. By failing to account for the value uplift, conventional cost-benefit analyses systematically underestimate the economic attractiveness of refurbishment. Incorporating building value after refurbishment into the assessment, even as a secondary KPI, provides a more complete and realistic picture and can shift the perceived viability of renovation measures.

The "hands-off period" emerged from stakeholder discussions as a KPI that, despite its simplicity, captures a highly relevant practical concern. It denotes the time span during which an energy system operates without requiring major reinvestment or strategic intervention. Its relevance is twofold. First, for both small and large housing companies, staff capacity for project planning and implementation is a binding constraint. Every energy system project demands management attention, technical coordination, and administrative effort. A longer hands-off period means that fewer projects need to be initiated over a given planning horizon, directly reducing the organizational burden. Second, the hands-off period influences investment cycles and capital allocation. A system that operates reliably for 20 years without major reinvestment needs frees up financial resources and management capacity for other portfolio activities.

Public subsidies and grant programs play a role that extends beyond merely improving the financial metrics of individual projects. As reflected in the secondary KPIs "share of total project costs covered by grants" and "share of capital costs covered by grants," grant funding is particularly valuable because it enables housing companies to pursue innovative energy concepts that would otherwise exceed their risk tolerance. By reducing the financial downside of novel approaches, such as large-scale heat pump systems, seasonal storage, or integrated sector-coupling configurations, grants allow organizations to gain practical experience with unfamiliar technologies. This learning effect is significant: once a housing company has successfully implemented and operated an innovative system, the perceived risk of subsequent projects decreases, and the technology may become part of the company's standard portfolio. Grant funding thus functions not only as a financial instrument but also as a catalyst for organizational learning and technological diffusion within the housing sector.

Beyond their technical purpose, several secondary KPIs also serve an important communicative function. Metrics such as the self-consumption rate or the self-sufficiency rate are intuitively understood by non-experts, including tenants and local stakeholders. A housing company can convey the value of a rooftop PV system far more effectively by stating that "60 % of the electricity generated on site is consumed within the district" than by presenting IRR figures. Similarly, grant coverage ratios are easily grasped and help communicate the financial support behind an investment. The ability to translate system performance into simple, relatable terms supports tenant and stakeholder acceptance. An aspect that, while not driving the investment decision itself, can facilitate its implementation.

Finally, we turn to KPIs that are not part of the framework but are nonetheless of interest and are frequently encountered in the literature. First, we deliberately excluded total energy production and total energy consumption as standalone KPIs, despite their frequent appearance in generic frameworks. From the investor's perspective, these absolute quantities are not directly actionable. They are largely determined by factors outside the investor's control, namely tenant behavior and the physical characteristics of the building stock. Moreover, their informational content is already embedded in other KPIs: total energy consumption is a key input to the LCOH calculation, while production volumes are reflected in self-consumption and self-sufficiency rates. Reporting them separately would add volume to the KPI set without adding decision-relevant insight, which runs counter to the framework's objective of maintaining a focused and prioritized indicator set.

The increasing electrification of heat supply and mobility leads to growing interdependence among the three energy sectors considered in this framework. Sector coupling, understood here primarily as the substitution of fossil energy carriers with electricity in heating and transport, fundamentally reshapes district energy systems. However, the degree of sector coupling or electrification does not constitute a target metric for economically motivated investors. No housing company optimizes for a higher degree of sector coupling per se. Instead, sector coupling is a structural characteristic of the system that emerges from technology choices driven by cost, regulation, and performance objectives. For this reason, no dedicated sector coupling KPI was included in the framework. Reporting the degree of electrification or sector coupling may nonetheless be useful as supplementary contextual information.

Closely related to sector coupling, flexibility is among the most frequently cited performance dimensions in the smart energy systems literature, encompassing a wide range of indicators related to demand response, load shifting, storage utilization, and grid interaction. Many of the analyzed papers include flexibility or smartness indicators, reflecting their focus on innovative, technology-driven energy solutions. From the perspective of the economically motivated investor, however, flexibility is not a value in and of itself. The ability to shift loads or switch between energy carriers is valuable when it enables the system to respond to variable renewable energy production, time-varying electricity prices, or regulatory signals such as grid usage constraints (e.g., §14a EnWG in Germany). In these cases, flexibility functions as a risk mitigation measure: a more flexible energy system can better adapt to changing market conditions, absorb regulatory requirements, and reduce exposure to price volatility. Importantly, many of the benefits commonly attributed to flexibility are already captured by existing KPIs in this framework. What flexibility adds beyond these indicators is an option value, the capacity to adapt system operation to uncertain future conditions. Quantifying this option value remains methodologically challenging and is an area for further research. It should also be noted that electrifying heat and mobility increases temporal flexibility by enabling load shifting across sectors but simultaneously increases dependence on a single energy carrier: electricity. This trade-off between operational flexibility and supply-side concentration risk warrants careful consideration in system design.

5. Conclusion

In this paper, we developed a stakeholder-specific KPI framework for residential district energy systems. Unlike generic frameworks that aim for broad applicability, the proposed approach is explicitly aligned with the decision logic of housing companies and housing cooperatives, as these actors ultimately determine whether and how energy system investments are implemented in residential districts. By distinguishing between primary and secondary KPIs, the framework establishes a clear hierarchy. Profitability indicators, most notably the IRR as the central metric, tenant cost metrics including warm rent and net rent, and emission-related measures constitute the core set of KPIs that directly inform investment decisions. The inclusion of rent as a primary KPI, while uncommon in the academic literature, emerged as essential from stakeholder interviews: for housing companies, the impact of any energy concept on tenant affordability and thus on vacancy risk is as decisive as its financial return. Secondary KPIs, covering aspects such as cost structures, building value, renewable energy integration, grant coverage, and peak loads, complement the assessment without overriding the primacy of primary decision criteria. Notably, widely used cost metrics such as CAPEX, OPEX, and TOTEX were classified as secondary indicators, as they serve as intermediate inputs that require further processing with investor-specific parameters before they become decision-relevant. Beyond their analytical function, several secondary KPIs, such as self-consumption rates and grant coverage ratios, also serve an important communicative role, translating system performance into terms that are intuitively understood by tenants and non-expert stakeholders.

The framework was developed through a literature review and subsequently refined through interviews with housing companies conducted after the initial framework design. Incorporating their feedback provides an indepth view of these actors' perspectives and decision-making processes. Moreover, it reveals implications for both science and policy by highlighting areas in which regulatory adjustments or targeted incentives may be required to better align private investment decisions with broader societal objectives. The discussion also highlighted the evolving role of housing companies, from pure heat providers toward multi-service energy actors offering electricity and EV charging, suggesting that metrics such as the LCOE and LCOC will gain importance in future framework revisions. Several commonly discussed dimensions, such as total energy production and consumption, flexibility, and sector coupling, were deliberately excluded. These aspects were omitted either because they lie largely beyond the direct influence of housing companies, because their informational content is already embedded in selected KPIs, or because they are not decision-relevant for these actors. Instead, they represent structural system characteristics or risk mitigation measures whose effects are already indirectly reflected in the selected KPIs. Their absence from an investor-oriented framework, however, carries a clear policy signal: where socially desirable outcomes, such as grid-supportive behavior or demand flexibility, lack a business case, external regulation or incentives are required to bridge the gap.

The framework intentionally focuses on the planning phase, during which decisions with multi-decadal consequences are made. Future research should extend the approach to the operational phase, where monitoring and adaptive management may require different KPI priorities. In addition, the quantification of flexibility as an option value and the integration of life-cycle-based environmental indicators represent promising avenues for further refinement. Finally, the transparent mapping of investor-relevant KPIs to policy objectives can support the design of more targeted and effective incentive structures for the energy transition in the residential sector.

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